WRITTEN CONTRIBUTIONS TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. I. J. Cohen: Some doubt has been expressed as to the practical robustness of loud-speakers constructed to conform to the specification given in the paper. Such loud-speakers have now been factory-constructed and put into use in private houses. Up to the present time (a period of about two years) no faults attributable to the loud-speakers themselves have been reported. Models have also been subjected to the usual dropping tests (in which the loud-speaker in its case is packed in a cardboard box, and allowed to fall from a height of 3 ft. on to a concrete floor, on each of its corners and faces), and the loud-speaker units have suffered no damage.

The dimensions of the "typical living room" chosen are slightly larger than those of the average living-room, and when one has to listen at a short distance from a loud-speaker having the "objective criterion" characteristics, the axial accentuation of the frequencies around 3 000 c./s. is noticeable. Have the authors considered the addition of some form of diffuser to widen the beam of radiation of the higher frequencies?

Dr. L. E. C. Hughes: As the authors suggest, the final test of any sound-reproducing system is an aural one, using the types of sound which are to be reproduced; in the broadcast relay system these will be any speech, music or noise, the latter being the most difficult to reproduce accurately. Because in a monaural system perfect

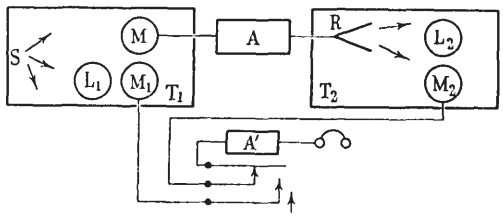

Fig. A

reproduction is not possible because of the inevitable increase in reverberation blur, it is necessary to take in a working definition of perfect reproduction samples of the original and reproduced sound, moving the microphone of the reproducing system so that a balance is obtained. Referring to Fig. A, to see whether the reproduction at the location of L_2 is a good copy of a selected

sample experienced by the listener L_1 to the original source of sound S when this is reproduced through any reproducing system M, A, R, it is necessary to compare aurally these two acoustic fields in such a way that the fickle memory of the ear is eliminated. It is likewise not entirely theoretically sound to try to have a duplicate source of sound in the reproducing chamber, chiefly because reproducing rooms are uncontrolled in that their period of reverberation is greatly different from the optimum for the type of material reproduced; no attempt is generally made to distribute the radiated sound in such a way as to simulate optimum conditions. To investigate whether such samples of original and reproduced sound can be made comparable, especially by shifting the microphone M of the reproducing system, it is clearly necessary to have two exactly similar microphones located at M_1 and M_2 and the outputs switched, preferably without breaking the circuit, through a high-grade reproducing system A_1, of quality at least equal to that of the system under test. The comparison system must clearly be highly free from blur of any kind and the listening must be on telephones, otherwise an additional reverberation blur would swamp any similar blur in the system under test. Such an aural comparator system, with two chambers, each about 4 000 cu. ft. in volume, with adjustable reverberations, T_1 and T_2, between about 0·6 and 3 sec., has been in use for some years at the City and Guilds College; under academic conditions this type of fundamental research is necessarily slow, but some results will shortly be published. The comparison microphones are moving-coil, such as were generally used by the B.B.C.; the head-telephones are also moving-coil. With this system the reverberation responses of various types of microphones and radiators can be studied subjectively, and the validity of technical criteria verified. To test one acoustic point, a pair of matched voices was discovered and used along the lines suggested by the authors, but this cannot be accepted as a general method. Using the comparison method it is generally possible to make good aural balances; it is actually a delicate adjustment and the listener must move the microphones remotely with strings. Once obtained, the balance is quite certain.

Although contrived long after the method of subjective assessment of the quality of reproduction of radio receivers for schools, as operated by the Approval (Apparatus) Sub-Committee of the Central Council for School Broadcasting, the latter's method is directly deducible from the theoretical method outlined above, except that the so-called standard radio receiver, which is properly used as a reference, replacing M_1 (there being a radio link in both test and reference circuits), is not of the highest quality obtainable, so that the testing committee of non-technical teachers can more easily decide where, on their subjective scale, the test receiver falls into place.

Mr. A. J. King: There is one feature of moving-coil loud-speaker design which appears to me to be very important from both the magnetic and acoustical points of view, and yet which seems to have been decided rather arbitrarily in the paper. I refer to the diameter of the moving coil, which is given as approximately 1 in. From the magnetic point of view a larger diameter is preferable, especially if a centre magnet of Alnico is used. This arrangement with a soft-iron yoke and pole-faces gives a good design with very low leakage if the gap mean diameter is of the order of 3 in. Such a diameter gives sufficient cross-section of Alnico to use it efficiently at its low operating flux density of 4 500 without the necessity for tapering the magnet down to the gap, a procedure which increases the leakage. For example, a centre pole 3 in. diameter and $\frac{1}{4}$ in. wide can be fed by a centre magnet $2\frac{3}{4}$ in. diameter with a 1-in. hole for convenience in assembly. The length of magnet naturally depends on the air-gap. From the acoustical point of view there is very little objection to the use of a coil of 3 in. diameter. The loss of area in the middle of even the small $7\frac{1}{2}$-in. cone described is a small percentage of the total area and is offset somewhat by a reduction in weight. The stress on the junction between moving coil and cone is reduced for a given output to approximately one-third. In addition the side of the cone is appreciably shorter and stiffer.

The arrangement has been tried and leads to a very sensitive loud-speaker which maintains its output to higher frequencies than with the same cone material and a small moving coil.

As regards sensitivity, a convenient check over the range where inertia-controlled piston movement can be assumed is one I described some years ago.* It consists of turning the loud-speaker so that its axis is vertical, and determining the minimum direct current through the moving coil which will just support the weight of the cone and coil. If this current is I mA and the projected area of the cone is A cm^2, it is easy to show, with the above simplifying assumptions, that the r.m.s. sound pressure developed at 1 m. from the cone per mA (r.m.s.) input to the coil is $0 \cdot 0019\ A/I$ dyne/cm^2/mA. There are obviously many factors of which this takes no account, but it is a good criterion of sensitivity in the medium-frequency range.

Flight-Lieut. M. G. Scroggie: Referring to the authors' subjective criterion of performance (Section 1.1), a programme sound which is heard directly is modified by the acoustics of the listening room. It will therefore be agreed that, when listening indirectly by means of a reproducing system that is perfect, the aural impression is as nearly as possible identical with the original when either studio or listening room *but not both* is acoustically similar to the direct listening room. The authors choose to introduce the acoustical effects at the listening end, the studio being "dead." At first sight this sounds reasonable, because in general it is more practicable for the studio to be controlled in this way than the domestic listening room. But in choosing thus, the authors have had to rule out just those types of programme that present the most interesting and complex problem in high-quality reproduction. The acoustical influence of surroundings is one of the dominant factors in the aesthetic enjoyment of programmes, making all the difference between a depressing experience and an inspiring one. It compensates also, in substantial degree, for loss of vision in dramatic broadcasts. It is only at the studio end that the necessary variations can be introduced. For testing purposes it is in general easier for the listener to move

* *British Radio*, 1929, **2**, p. 76.

himself from a studio, which is either the direct listening room or its equivalent, to a " dead " indirect listening room, than to transfer the source of sound as described in the paper. The former method enables the comparison to be carried out with all types of programme, including dramatic or large-scale concert performances.

In studying the influence of the listening room, tests were carried out in rooms described as typical but which seem to be decidedly exceptional both in shape and size. A height of 11 ft. 6 in. must be well above the average for domestic rooms, and volumes approximately half of those specified would probably be nearer the average.

In the formula for calculating the mean spherical sound pressure (Section 2.1) it would appear to be more satisfactory to select test angles which would give *equal* concentric divisions of space. It is not clear that there is any justification for giving so much less weight to the data for axial radiation than to others.

The exclusive concentration on frequency distortion in loud-speakers is at least open to question. The ear must necessarily be very tolerant of frequency distortion, because of the very large variations in frequency characteristics introduced by the acoustics of different listening rooms. On the other hand, the ear is extremely sensitive to alien tones. A slight " buzz " in a loud-speaker renders reproduction well-nigh intolerable yet may not be revealed at all by a frequency test. Moving-coil loud-speakers of typical construction have often been shown to introduce frequency-halving, frequency-doubling, and transient distortion due to oscillatory " hangover." In this connection one could wish that the authors had not entirely ignored the impedance out of which the loud-speaker has to work.

Finally, with reference to the last paragraph in Section (6), the authors' views on the double-cone type of construction for improving high-note response would be welcomed.

Mr. D. R. Turner: The authors have utilized what they consider to be a typical living-room, and by means of tests carried out in it have arrived at certain conclusions as to the most desirable characteristics for loud-speakers for use in living-rooms. However, the room chosen for this purpose was considerably larger than the majority of living-rooms and I would suggest that a room 15 ft. by 12 ft. by 9 ft. high, or slightly smaller, would be more " typical." In view of this do not the authors consider that it would be advisable to carry out supplementary tests in a smaller room in order to determine whether the room size will materially modify the speaker characteristics required for faithful reproduction?

It is stated that the object of the investigations was to design a speaker which would, among other requirements, be inexpensive, and that samples submitted by contractors were satisfactory both as to performance and price. As the price of loud-speakers varies over a very wide range, it would be interesting to know into what portion of this range the prices of these samples fall.

The bad practice of fitting the radio receiver and loud-speaker in one cabinet is not mentioned in the paper. Do the authors consider that the evil effects of this practice could be lessened to any extent by the use of damping materials in the cabinet?

Mr. P. G. A. H. Voigt: The experience that abnormal room acoustics can have a surprising effect is one that is often encountered when demonstrating high-quality reproducing apparatus, and is also familiar to organ builders, who usually " voice " their instruments on site for this reason. It is unfortunate that many modern rooms with hard plaster surfaces and therefore excessive treble reverberation have cavity walls which absorb the bass, thus aggravating the trouble. The thick walls covered with soft plaster often found in old houses have the reverse effect, especially if the room is heavily carpeted, has upholstered furniture and heavy curtains. In this connection it is important to note that with a defective reverberation curve the energy relation of different frequencies will change as a note decays. " Cooking " the frequency response of the amplifier, etc., can only be regarded as a useful method of partially hiding one fault by introducing another; it can never be a real cure, since no amount of " cooking " can prevent the change in tone colour as a sound dies away.

When calibrating, even with a warble tone, violent differences in loudness are to be expected as between different positions under live conditions, especially at the lower end of the frequency spectrum. That an average of 9 readings may differ from an average of 54 by as much as 10 db. is, however, very surprising, and I hope that the authors can give us more information about these special cases. In view of the fact that the 9 positions in the frame are geometrically related, it seems feasible that at certain low frequencies their pattern may happen (especially if near the walls) to fit the mean stationary wave pattern of the warble tone. If under such conditions all 9 positions are situated simultaneously in nodes or antinodes for stationary-wave patterns in different directions, the most violent departures from average loudness could occur.

Another possibility is that the frame might correspond to the average listening position, i.e. in front of the loud-speaker near the axis, and therefore come within the high-frequency beam. Measurements in this position would naturally show a treble response considerably above the average.

It is my experience that the actual response in the direction of the listener has some effect, and that the comfort of listening is greatly enhanced if concentration of high frequencies is prevented, so that direct and reflected sounds approximate in composition. It is a pity that various considerations (presumably, mainly that of cost) prevented the inclusion of means for spreading the beam, thus compelling the study of a system which is inherently " beamy " and can therefore never become perfect no matter how carefully the relation between axial and average response is established.

I hope that the authors will stress the fact that the characteristic which they have deduced, namely a slope of $2\frac{1}{2}$ db. per octave, is only an approximation which happens to fit their particular dimensions fairly closely. Actually, as they say on page 60, Section (3.2), the radiation is spherical at low frequencies. At these frequencies, therefore, the axial response will equal the average response, and if this latter is uniform the axial response will be uniform also. This is confirmed by the readings below 300 c./s. plotted in Fig. 2 (crosses), which lie nearly on a horizontal line. If the curve is

drawn through these points, i.e. zero slope per octave up to 300 c./s., and then continued through the other points it will curve upward (in a region actually determined by the dimensions of the sound source) and then rise more steeply than $2\frac{1}{2}$ db. per octave. The true curve relating axial to total radiation is therefore more complicated than a single straight line. Between 100 and 3 000 c./s., however, a line sloping at $2\frac{1}{2}$ db. per octave lies so near the more complicated curve that the authors are quite justified in adopting the simpler curve for their particular purpose.

The curves published are taken with constant voltage on the grid of the power valve. Under laboratory conditions a triode whose internal resistance might be about one-quarter the optimum load would probably be used. With a pentode, the curve would be different unless the impedance curve (not published) happened to be level. I should like to have some more information on this point.

It is usual for a loud-speaker impedance curve to rise considerably in the bass; this mismatching (when used with triodes) causes the speaker to reject low frequencies and may account in part for the fact that in spite of a resonance as low as 30 c./s. the output diminishes rapidly below 100 to 200 c./s.

With regard to the design of the coil, the use of an extra half-turn would seem to introduce a lop-sided factor, because that half of the coil with the extra half-turn, although heavier, would be subject to increased forces. The effect of the extra force could be avoided by winding the additional half-turn on the speech-coil tube outside the gap. From the fact that the authors have not found this necessary, I take it that the effect is negligible.

The spider is mentioned as a possible source of trouble. One manufacturer has used damping pads, presumably to prevent this. Have the authors found anything special to be necessary?

Their experience with various apparently similar cones is most interesting. I have found that the surround may have a marked effect of a similar kind at high frequencies, and have therefore concluded that wave reflection up and down the cone can occur. If the material of the cone itself can be made to absorb energy, such a stationary wave would be damped. I should therefore be interested to know whether any experiments are contemplated to ascertain whether differences in internal damping of the cone material account for the differences in response experienced between apparently similar diaphragms.

No mention is made of the preferred position for the loud-speaker. I think that it is most undesirable to have it near the floor. What is the authors' opinion?

Finally, are any steps taken to prevent the felt from becoming a breeding place for moths, and if so does the treatment affect its sound-absorbing properties?

Messrs. A. K. Webb and **R. C. G. Williams:** The authors have published a paper which will be of value to all those interested in the art of reproduction, both in view of the novel features embodied in the design and the original angle from which the problem has been approached. We have, however, a number of comments to make, based on practical experience, which can conveniently be grouped under four headings as follows:—

(*A*) *Variation of response with position of observer.*

The design of the loud-speaker unit described in the paper is based on the assumption that acoustic power output should be constant throughout the frequency range considered (for a constant input). We agree in general with this conclusion, but would suggest one most important qualification arising from the fact that the ear is a pressure-operated device, capable of assessing sound intensity at a particular point but not capable of averaging intensity over a considerable area.

It seems essential that a loud-speaker of the type described, having a constant mean spherical response, should be rendered substantially non-directional when used under normal home conditions, for the conventional position of the observer in a small room, relative to the loud-speaker, is such that he will hear a fairly high proportion of direct to reflected sound, and therefore the polar distribution of the unit is an important consideration. In this particular design, calling for a rising axial response, the listener will be apt to complain of shrillness when listening under near-axial conditions. It is felt, therefore, that some form of mechanical diffuser should be incorporated in front of the diaphragm, or the unit should be so placed in the room that the observer must be well off the axis at all times. These precautions are not necessary with the average loud-speaker, where axial response is held approximately constant. It is true that there is a lack of " top " off the axis, but this is, as it were, a negative effect, and does not cause discomfort to the ear.

(*B*) *Variation of axial and mean spherical response with frequency.*

It is agreed that a definite relation can be established between axial and mean spherical response, for a given loud-speaker. The authors state that for constant mean spherical response an axial curve rising a given number of decibels per octave is required over the frequency range covered by this loud-speaker. As we understand it, the difference between axial and mean spherical response is a function of the focusing effect of the diaphragm, where its diameter becomes comparable with the wavelength of sound reproduced. In this event a practical case should show a decreasing difference between the two responses below, say, 500 c./s. A study of Figs. 1 and 2 would seem to bear out this hypothesis. In Fig. 1, axial and mean spherical responses are seen to coincide closely from 100 to 500 c./s., while the plotted points of Fig. 2 also indicate that the ratio of axial to mean spherical sensitivity can be regarded as constant over this range. The result, then, of designing the loud-speaker to have a steadily rising axial response of 2·5 db. per octave would seem to be the introduction of a progressive bass loss below 500 c./s.

(*C*) *Frequency response of curved diaphragms.*

With regard to the response variations possible when using various types of moulded paper cone, we would point out that 8-in. diameter curvilinear diaphragms have been developed for commercial use, having a response maintained up to 8 000 c./s., with a maximum

deviation of $\pm$ 2·5 db., the general slope being dependent upon the ratio of diaphragm to speech-coil mass, and the variation of speech-coil current with frequency. (In this connection it would be interesting to know the exact method of feeding the speech coil in the authors' investigation, as this obviously has a profound effect on the responses obtained.)

As the diameter of the curved diaphragm is reduced below 8 in., however, the response becomes increasingly peaky, and we have not yet succeeded in developing a sample that can be regarded as satisfactory from all points of view. This lines up with the authors' findings.

(*D*) *Other factors.*

The efficiency of the unit will be less than that of the average quality speaker, both as a result of enclosing the back and specifying a flux density of 6 000 lines per cm^2, which we regard as rather low. The fact that the speech coil is only 10 % longer than the gap will tend to limit undistorted output severely, and it is felt that harmonic distortion in the bass, together with attendant intermodulation, will be noticeable at moderate output levels.

In the light of practical experience we forecast that quantity production will be somewhat hazardous and expensive, in view of the method of cone suspension and the small speech-coil clearances allowed.

Finally, we notice that the speech-coil lead-off wires are a continuation of the winding. This small-diameter solid wire will be somewhat liable to breakage due to continual flexure while in use, therefore we would recommend that the leads from the coil be run a short distance up the cone and eyeleted thereto. The lead-off wires can then be of the conventional copper-tinsel type.

Messrs. W. West and **D. McMillan** (*in reply*): Mr. Cohen has drawn attention to a very important aspect of design, namely reliability in service. His remarks remind us of the considerable amount of criticism, based on manufacturing experience, which has been received and welcomed by us as helpful. Much of this criticism has not, however, been substantiated in practice. Some of the remarks in Section (D) of Messrs. Webb and Williams's contribution seem to fall into this category. We are also reminded of the lapse of time—about three years—since the investigation was carried out. At that time the axial response of the "average loud-speaker" was anything but constant; we gather from Messrs. Webb and Williams's remarks that it is now approximately constant, though this is not quite the impression we have received from such casual listening as has come within our experience.

Several contributors to the discussion have referred to the fact that the rooms we used were larger than typical living-rooms. It is, however, absorption rather than size of the room that is of importance. The conclusion that the mean-spherical response is the proper criterion to use was based fundamentally on the hypothesis that at most listening positions the reverberant sound preponderates over the direct sound. Since these two sounds cannot readily be separated, the average sound-pressure tests were made to confirm the hypothesis. These tests were made almost entirely between radii of 4 and 12 ft. from the loud-speaker, and for the most part less than 10 ft., to include all usual listening positions relative to the loud-speaker. Now if the surfaces of the room had been brought nearer, i.e. the room made smaller, the proportion of reverberant to direct sound could not have been decreased thereby. Consequently the general conclusion reached for the larger rooms will apply also to smaller rooms. It will not, of course, apply equally to all rooms and all individual listening positions, and if the listening position is close to the loud-speaker, on the axis, or if the room has little absorption on any of the vertical surfaces (the direction of the high-frequency beam from the loud-speaker being assumed to be horizontal), some accentuation of the high frequencies will be noticed. Room Y is a case in point, but even for this room uniformity of mean spherical sound pressure is a better criterion than that of axial sound pressure. Mr. Voigt has remarked on the unfortunate tendencies of the acoustics of some modern rooms and furniture, but loud-speaker design should not be influenced by faulty room acoustics.

Mr. Cohen, and others, have suggested the use of a diffuser to spread the high-frequency beam, and we agree that such is desirable, not only for this loud-speaker but for all that are in common use in living-rooms. This question was considered during the investigation but it was evident that an appreciable increase in cost, and probably also in bulk, would be involved; so further consideration was deferred to a later stage of development, if and when opportunity offered. Meanwhile the user has, under his control, adjustment of the direction in which the loud-speaker is oriented with respect to the usual listening positions in the room. The effect of such adjustment is not generally very noticeable.

Finding some difficulty in understanding the purport of Dr. Hughes's remarks, we shall look forward with interest to further disclosures in the publication which he forecasts. It appears that the subjective criterion which Dr. Hughes seeks to apply is that the reproduced sound in Room 2 (Fig. A) should resemble as closely as possible the original sound as heard in Room 1. This is not a criterion which can be capable of general practical application, nor is it in our view so worth while as the one we have suggested. The limitation to a "monaural" transmitting system is not an obstacle to the attainment of perfect reproduction of a single source of sound, though of course, where several sources are operating simultaneously, they must all emanate in the reproduction from a single point in the room—the loud-speaker.

Mr. King is correct in supposing that the diameter of the moving coil was chosen by us rather arbitrarily. We saw no need to go into the question of magnet design and made use of types from commercial production. The size was in very common use by manufacturers and we were therefore able to examine the performance of a large number and variety of samples of cones on the same experimental mounting. Perhaps the most interesting feature of the large coil design which Mr. King has described lies in his suggestion that response over a wider range of frequencies can thereby be obtained from the cone. Messrs. Webb and Williams regard 6 000 lines per cm^2 as being rather low, but this figure was quoted as the minimum value for specification purposes; since sufficient sensitivity for the purpose required could be obtained therefrom, there was no point in making the

specification more severe, though it was stated that sensitivity would be one of the factors to be considered in the placing of any contract resulting from the submission of contractors' samples. The statement that enclosing the back of the loud-speaker reduces its efficiency needs some qualification, as it has been demonstrated that over a useful range of low frequencies it has the reverse effect.

Flight-Lieut. Scroggie prefers the method of comparison in which the listener moves between studio and listening room, to the one in which the source of sound is transferred. For some purposes, such as the placing of microphones or arrangement of studio for particular items, the method he prefers is the best, if not the only practicable one; but for the design of a loud-speaker it involves the sacrifice of a tangible standard. Flight-Lieut. Scroggie's objection to the standard which we suggest lies in the necessary restriction (for the design of a loud-speaker) to sources of sound which could by nature be heard in the listening room. He offers no alternative meaning to the phrase " faithful reproduction," which is generally recognized as the desirable objective of design but which will never be attained unless it has a definite and real significance. We do not think that aesthetic considerations should enter into the design for performance of a loud-speaker; they are proper to the production of the sounds, to adjustments of the acoustics of the rooms and to locating microphones for individual programme items, but not to the transmitting or reproducing system. They are not allowed to enter into the design of microphones or amplifiers and there is no justification for making an exception in the case of loud-speakers. Nothing is really lost by restricting comparison (for assessing performance of the system) to individual sources of sound; there is a sufficiently wide variety readily available and the basis of comparison is unequivocal. With a system that is near to perfection on this basis and with a studio technique based on a comparison of the kind that Flight-Lieut. Scroggie advocates, using a " typical " listening room for monitoring, the best results possible for the listening room concerned will have been achieved.

Perhaps the interpretation of " faithful reproduction " which we are using can help to answer Mr. Voigt's question about the preferred position of a loud-speaker. For individual sources of sound, e.g. the speaking voice, it is required that the reproduction shall sound as though the original source were in the room. To assist the illusion it is clearly helpful that the sound should come from a point in the room which could naturally be occupied by the originating source. From this aspect there certainly is objection to allowing the sound to come from the floor.

We agree with Flight-Lieut. Scroggie that frequency distortion is by no means the only factor to consider in the performance of a loud-speaker; it was, however, the outstanding weakness of ordinary design,* and our attempts to eliminate this weakness are the justification, or excuse, for this paper. Other factors were not ignored by us, but further possibilities of improvement were relegated to consideration at a later stage of development, when time had permitted a proper sense of proportion to be acquired of the various possible imperfections remaining in the performance of the manufactured product. We regret that circumstances have so far prevented further work by us on this problem. The generation by the loud-speaker of inharmonic tones, or " buzz," certainly deserves serious attention; the spider is perhaps the usual cause of the most noticeable manifestations. We did not attempt at this stage to specify particular means for avoiding this trouble, since many manufacturers' products are reasonably free from it. Mr. Voigt mentions damping pads; if these are effective in practice the idea is sound, so also is a reduction in mass of the parts of the spider which can vibrate in unwanted modes of vibration. In our design a contribution of stiffness by the spider is not required and a very light construction should therefore be possible. The desirability of avoiding tension was mentioned in the paper.

It is not likely that the suggestion to select test angles giving equal divisions of space for calculating mean spherical sound pressure would give a better average than testing at equal angles—for the same number of test points. At the lower frequencies the readings at 30° and 60° are almost as large as those on the axis, while at the higher frequencies the influence of tests at other angles is small. If angles giving equal divisions of space were used, less data would be obtained of the concentrating of the beam at the higher frequencies, since the nearest test angle to the one on the axis would be much greater than 30°.

We received no ready-made samples of the double-cone type of diaphragm mentioned by Flight-Lieut. Scroggie, and we did not, in the present stage of development, initiate any experiments with this type of construction because of the greater cost likely to be involved. We were rather doubtful whether a mechanically coupled radiating system of this kind could be made to produce so smooth a frequency-characteristic as has been obtained from a simple diaphragm.

In reply to Mr. Turner's question on price, it can reasonably be stated that the quotations we mentioned compared favourably with prices for loud-speakers supplied to relay companies. We see no great objection to fitting a loud-speaker in the same cabinet as a radio receiver, if it is done without sacrificing the performance of either. The loud-speaker would require a separate division in the cabinet if it has an enclosing case—as we advocate—since it is undesirable from the points of view of maintenance and heat dissipation to enclose the radio receiver.

The " $2\frac{1}{2}$ db. per octave " rule is purely empirical and, as Mr. Voigt correctly states, is intended only as an approximation. It is used as a convenient guide to the main objective, namely a uniform frequency characteristic of mean spherical radiation. We also expected at low frequencies the decrease of slope, asymptotic to the horizontal, to which Mr. Voigt refers, but we did not consider that the results of Fig. 2 justified the complexity involved in altering slightly the simple rule, in the present state of the art of controlling the frequency characteristics of loud-speakers. Messrs. Webb and Williams have also raised this question but we think that they have exaggerated the difference to be expected. At 500 c./s., and even at considerably lower frequencies, the distribution of radiation has become markedly distorted from the

spherical shape. It is not only the size of the cone, but also the size of the loud-speaker, relative to a wavelength, that contributes to the effect.

As Mr. Voigt has supposed, triode amplification was used in the power stage feeding the loud-speaker; the investigation did not include experiments with different types of amplifier or circuit connecting the loud-speaker. Table A shows the impedance variations of a loud-speaker made to the specification. No marked irregularities were noticed at frequencies intermediate between those stated.

Table A

Frequency	Impedance	Angle	Frequency	Impedance	Angle
c./s. 70	ohms 3·3	—	c./s. 400	ohms 2·4	+ 7°
100	3·2	− 12°	600	2·6	+ 20°
120	2·7	− 13°	1 000	3·1	+ 31°
150	2·4	− 6°	2 000	4·4	+ 42°
200	2·3	0	5 000	7·4	+ 50°
300	2·4	+ 10°	7 000	9·3	+ 52°

The resonance at 30 c./s. (mentioned in Section 5.2) relates to the loud-speaker unit only; when the unit is assembled in the case, the resonance frequency is raised to somewhat over 100 c./s.—for the particular size of case specified. This accounts for the diminishing output at lower frequencies.

The answer to the question on moths is simply that, with a gauze cover over the aperture in the front of the case, access for moths is prevented.

We regret that we are not now in a position to give Mr. Voigt further information with regard to the very exceptional cases of large errors in the average of 9 readings, mentioned in Section (2.2). These errors are somewhat greater than can be expected with a normal error distribution, and it is possible that the results may have been influenced by the causes which Mr. Voigt suggests.

We have not made direct tests of internal damping of different cone materials, but we regard it as a helpful factor for obtaining a smooth frequency characteristic.* The mechanical tests mentioned in Section (4.6) can perhaps be regarded as confirmatory, since increased internal damping can be expected with a weaker moulding of the paper, the small fibres being less firmly bonded together.

* See W. West: "Acoustical Engineering," pp. 166 and 167 (London, 1932).